Chapter 8

REFRIGERATED CONDENSERS

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8.1 Introduction

Condensers in use today may fall in either of two categories: refrigerated or non-refrigerated. Non-refrigerated condensers are widely used as raw material and/or product recovery devices in chemical process industries. They are frequently used prior to control devices (*e.g.*, incinerators or absorbers). Refrigerated condensers are used as air pollution control devices for treating emission streams with high VOC, concentrations (usually $>$ 5,000 ppmv) in applications involving gasoline bulk terminals, storage, etc.

Condensation is a separation technique in which one or more volatile components of a vapor mixture are separated from the remaining vapors through saturation followed by a phase change. The phase change from gas to liquid can be achieved in two ways: (a) the system pressure can be increased at a given temperature, or (b) the temperature may be lowered at a constant pressure. In a two-component system where one of the components is noncondensible (*e.g.*, air), condensation occurs at dew point (saturation) when the partial pressure of the volatile compound is equal to its vapor pressure. The more volatile a compound (*i.e.*, the lower the normal boiling point), the larger the amount that can remain as vapor at a given temperature; hence the lower the temperature required for saturation (condensation). Refrigeration is often employed to obtain the low temperatures required for acceptable removal efficiencies. This chapter is limited to the evaluation of refrigerated condensation at constant (atmospheric) pressure.

8.1.1 System Efficiencies and Performance

The removal efficiency of a condenser is dependent on the emission stream characteristics including the nature of the VOC in question (vapor pressure/temperature relationship), VOC concentration, and the type of coolant used. Any component of any vapor mixture can be condensed if brought to a low enough temperature and allowed to conic to equilibrium. Figure 8.1 shows the vapor pressure dependence on temperature for selected compounds.[1] A condenser cannot lower the inlet concentration to levels, below the saturation concentration at the coolant temperature. Removal efficiencies above 90 percent can be achieved with coolants such as chilled water, brine solutions, ammonia, or chlorofluorocarbons, depending on the VOC composition and concentration level of the emission stream.

8.2 Process Description

Figure 8.2 depicts a typical configuration for a refrigerated surface condenser system as an emission control device. The basic equipment required for a refrigerated condenser system includes a VOC condenser, a, refrigeration unit(s). and auxiliary, equipment (*e.g.*, precooler, recovery/storage tank, pump/blower, and piping).
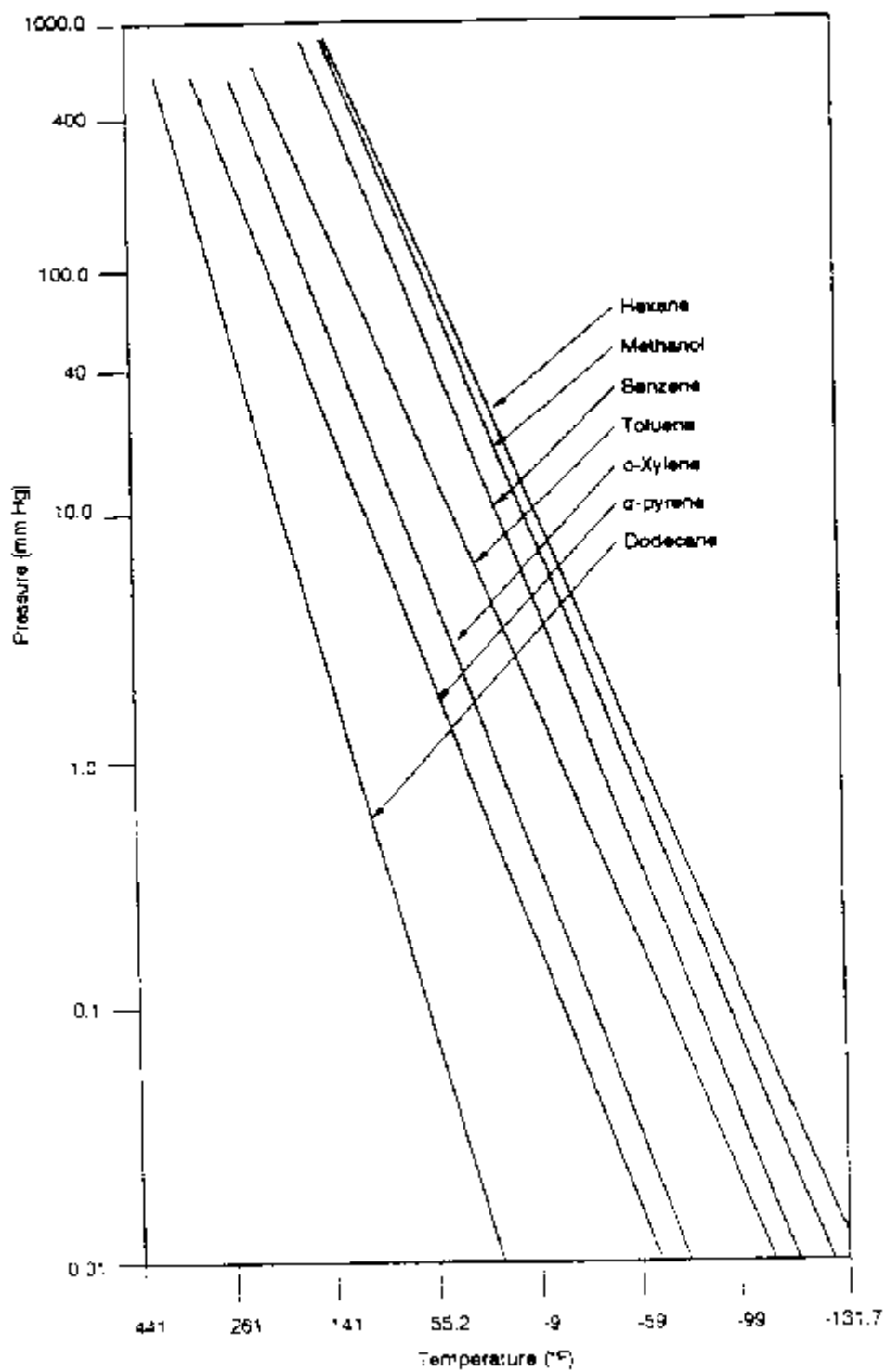
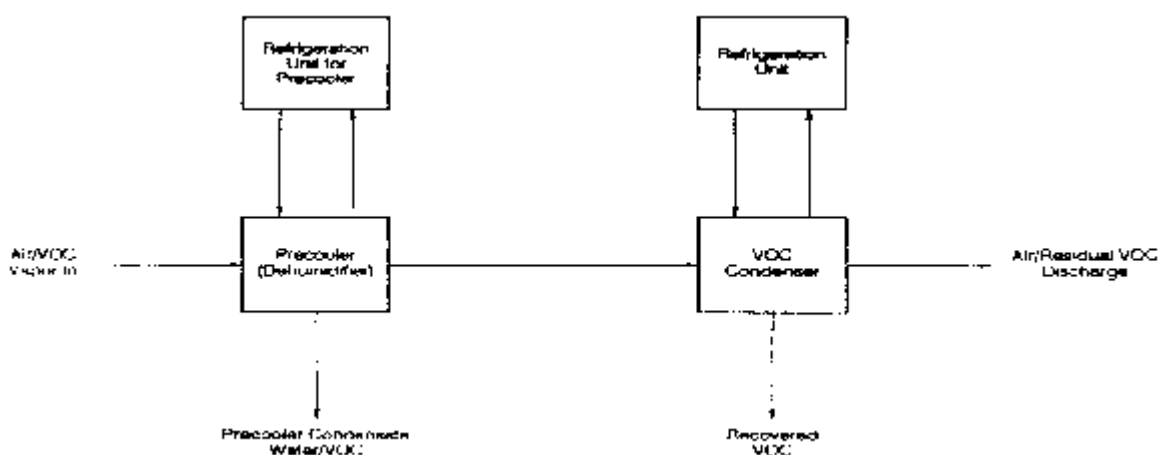**Figure 8.1**: Vapor Pressures of Selected compounds vs. Temperature[1]

Figure 8.2: Schematic Diagram for a Refrigerated Condenser System

8.2.1 VOC Condensers

The two most common types of condensers used are surface and contact condensers. [21 In surface condensers, the coolant does not contact tile gas stream. Most surface condensers in refrigerated systems are the shell and tube type (see Figure 8.3). [3] Shell and tube condensers circulate the coolant through tubes. The VOCs condense on the outside of the tubes (*i.e.*, within the shell). Plate and frame type heat exchangers are also used as condensers in refrigerated systems. In these condensers, the coolant and the vapor flow separately over thin plates. In either design, the condensed vapor forms a film on the cooled surface and drains away to a collection tank for storage, reuse, or disposal.

In contrast, to surface condensers where the coolant does not contact either the vapors or the condensate, contact condensers cool tile vapor stream by spraying either a liquid at ambient temperature or a chilled liquid directly into the gas stream.

Spent coolant containing the VOCs from contact condensers usually can not be reused directly and can be a waste disposal problem. Additionally, VOCs in the spent coolant can not be directly recovered without further processing. Since the coolant from surface condensers does not contact the vapor stream, it is not contaminated and can be recycled in a closed loop. Surface condensers also allow for direct recovery of VOCs from tile gas Stream. This chapter addresses the design and costing of refrigerated surface condenser systems only.
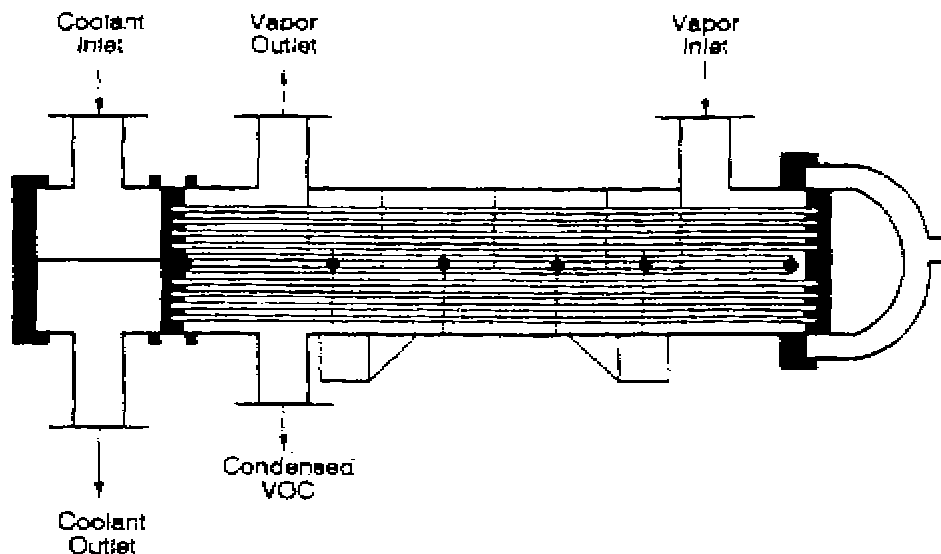
Figure 8.3: Schematic Diagram for a Refrigerated Condenser System

8.2.2 Refrigeration Unit

The commonly used mechanical vapor compression cycle to produce refrigeration consists of four stages: evaporation, compression, condensation, and expansion (see Figure 8.4).[4] Tile cycle which is used for single-stage vapor compression involves two pressures, high and low, to enable a continuous process to produce a cooling effect. Heat absorbed from tile gas stream evaporates the liquid coolant (refrigerant). Next, the, refrigerant (now in vapor phase) is compressed to a higher temperature and pressure by tile system compressor. Then, the superheated refrigerant vapor is condensed, rejecting its sensible and latent heat in the condenser. Subsequently, the liquid refrigerant flows from the condenser through the expansion valve, where pressure and temperature are reduced to those in the evaporator, thus completing the cycle.

The capacity of a refrigeration unit is the rate at which heat is removed, expressed in tons of refrigeration. One ton of refrigeration is the refrigeration produced by melting one ton of ice at 32°F in 24 hours. It is the rate of removing heat equivalent to 12,000 Btu/h or 200 Btu/min. For more details on refrigeration principles, see References [5] and [6].

Applications requiring low temperatures (below about -30°F), multistage refrigeration systems are frequently employed.[4] Multistage systems are designed and marketed in two different types-compound and cascade. In compound systems, only one refrigerant is used. In a cascade system, two or more separate refrigeration systems are interconnected in such a manner that one provides a means of heat rejection for the other. Cascade systems are desirable for applications requiring temperatures between -50 and -150°F and allow the use of different refrigerants in each cycle.[4] Theoretically, any number of cascaded stages are possible, each stage requiring an additional condenser and an additional stage of compression.

In refrigerated condenser systems, two kinds of refrigerants are used, primary and secondary. Primary refrigerants are those that undergo a phase change from liquid to gas after absorbing heat. Examples are ammonia (R-717), and chlorofluorocarbons such as chlorodifluoromethane (R-22)
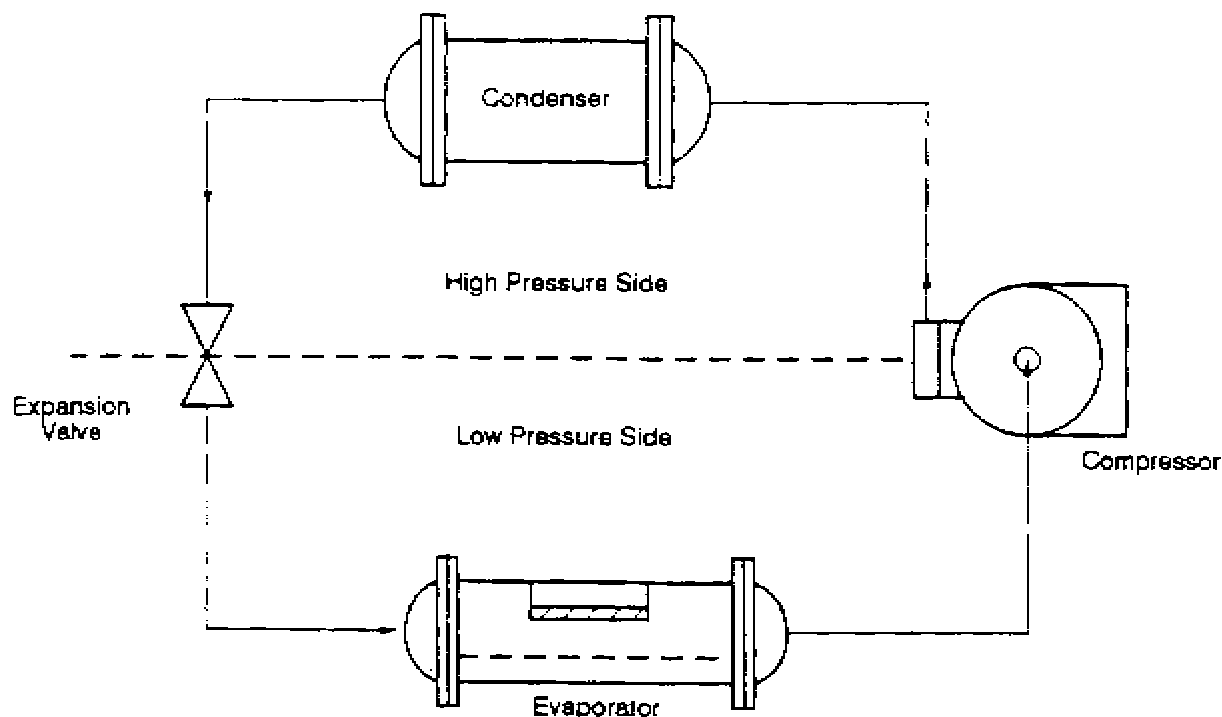
Figure 8.4: Basic Refrigeration Cycle [4]

or dichlorodifluororrmethane (R-12). Recent concerns about the latter causing depletion of the ozone layer is prompting development of substitute refrigerants.

Secondary refrigerants such as brine solutions act only as heat carriers and remain in liquid phase. Conventional systems use a closed primary refrigerant loop that cools the secondary loop through the heat transfer medium in the evaporator. The secondary heat transfer fluid is then pumped to a VOC vapor condenser where it is used to cool the, air/VOC vapor stream. In some applications. however, the primary refrigeration fluid is directly used to cool the vapor stream.

8.2.3 Auxiliary Equipment

As shown in Figure 8.2, some applications may require auxiliary equipment such as precoolers, recovery/storage tanks, pumps/blowers, and piping.

If water vapor is present in the treated gas stream or if the VOC has a high freezing point (*e.g.*, benzene), ice or frozen hydrocarbons may form on the condenser tubes or plates. This will reduce the heat transfer efficiency of the condenser and thereby reduce the removal efficiency. Formation of ice will also increase the pressure drop across the condenser. In such cases, a precooler may be needed to condense the moisture prior to the VOC condenser. This precooler would bring the temperature of the stream down to approximately 35 to 40°F, effectively removing the moisture from the gas. Alternatively, an intermittent heating cycle can be used to melt away ice build-up. This may be accomplished by circulating ambient temperature brine through the condenser or by the use of radiant heating coils. If a system is not operated continuously, the ice can also be removed by circulating ambient air.

A VOC recovery tank for temporary storage of condensed VOC prior to reuse, reprocessing, or transfer to a larger storage tank may be necessary in some cases. Pumps and blowers are typically used to transfer liquid *(e.g.,* coolant or recovered VOC) and gas streams, respectively, within the system.

8.3 Design Procedures

In this section are presented two procedures for designing (sizing) refrigerated surface condenser systems to remove VOC from air/VOC mixtures. With the first procedure presented, one calculates the condenser exit temperature needed to obtain a given VOC recovery efficiency. In the second procedure, which is the inverse of the first, the exit temperature is given and the recover efficiency corresponding to it is calculated.

The first procedure depends on knowledge of the following parameters:

1. Volumetric flow rate of the VOC-containing gas stream;

2. Inlet temperature of the gas stream;

3. Concentration and composition of the VOC in the gas stream;

4. Required removal efficiency of the VOC;

5. Moisture content of the emission stream; and

6. Properties of the VOC (assuming the VOC is a pure compound):
    • Heat of condensation,
    • Heat capacity, and
    • Vapor pressure.

The design of a refrigerated condenser system requires determination of the VOC condenser size and the capacity of the refrigeration unit. For a given VOC removal efficiency, the condensation temperature and the heat load need to be calculated to determine these parameters. The data necessary to perform the sizing procedures below as well as the variable names and their respective units are listed in Table 8.1.

Table 8.1: Required Input Data

Data	Variable Name	Units
Inlet Stream Flow Rate	Q_{in}	scfm (77°F; 1 atm)
Inlet Stream Temperature	T_{in}	°F
VOC Inlet Volume Fraction	$y_{voc,in}$	volume fraction
Required VOC Removal Efficiency	η	fractional (volume)
Antoine Equation Constants[a]	A,B,C	-
Heat of Condensation of the VOC[a]	ΔH_{voc}	Btu/lb-mole
Heat Capacity of the VOC[a]	$C_{p,voc}$	Btu/lb-mole-°F
Specific Heat of the Coolant	$C_{p,cool}$	Btu/lb-°F
Heat Capacity of Air	$C_{p,air}$	Btu/lb-mole-°F

[a]See Appendix 8A for these properties of selected organic compounds.

The steps outlined below for estimating condensation temperature and the heat load apply to a two-component mixture (VOC/air) in which one of the two components is considered to be noncondensible (air). The VOC component is assumed to consist of a single compound. Also, the emission stream is assumed to be free of moisture. The calculations are based on the assumptions of ideal gas and ideal solution to simplify the sizing procedures. For a more rigorous analysis, See Reference [5].

8.3.1 Estimating Condensation Temperature

The temperature necessary to condense the required amount of VOC must, be estimated to determine the heat load. The first step is to determine the VOC concentration at the outlet of the condenser for a given removal efficiency. This is calculated by first determining the partial pressure of the VOC at the outlet assuming that the ideal gas law applies:

$$VOC\ partial\ pressure\ (outlet)\ = 760\ \frac{Moles\ VOC\ in\ outlet\ stream}{Moles\ inlet\ stream\ -\ Moles\ VOC\ removed} \qquad (8.1)$$

However:

$$\text{Moles VOC in outlet stream} = (\text{Moles VOC in inlet stream})(1 - \eta) \qquad (8.2)$$
$$\text{Moles VOC in inlet stream} = (\text{Moles in inlet stream})\ y_{voc,in} \qquad (8.3)$$
$$\text{Moles VOC removed} = (\text{Moles VOC in inlet stream})\eta \qquad (8.4)$$

where

η = removal efficiency of the condenser system (fractional)
= Moles VOC removed/Moles VOC in inlet
$y_{voc,in}$ = Volume fraction of VOC in inlet stream

After substituting these variables in Equation 8.1, we obtain:

$$P_{VOC} = 760 \frac{y_{VOC,in}(1-\eta)}{1-y_{VOC,in}(\eta)} \tag{8.5}$$

where

P_{VOC} = Partial pressure of the VOC in the exit stream (mm Hg).

The condenser is assumed to operate at a constant pressure of one atmosphere (760 mm Hg).

At the condenser outlet, the VOC In the, gas stream is assumed to be at equilibrium with the V0C condensate. At equilibrium, the partial pressure of the VOC in the gas stream is equal to its vapor pressure at that temperature assuming the condensate is pure VOC (*i.e.*, vapor pressure P_{voc}). Therefore, by determining the temperature at which this condition occurs, the condensation temperature can be specified. This calculation is based on the Antoine equation that defines the relationship between vapor pressure and temperature for a particular compound:

$$\log(vapor\ pressure) = \log P_{VOC} = A - \frac{B}{T_{con}+C} \tag{8.6}$$

where T_{con} is the condensation temperature (°C). Note that T_{con} is in *degrees Centigrade* in this equation. In Equation 8.6, *A, B,* and *C* are VOC-specific constants pertaining to temperature expressed in °C and pressure in mm Hg (see Appendix 8A). Solving for T_{con} and converting to degrees Fahrenheit:

$$T_{con} = \left(\frac{B}{A-\log_{10} P_{VOC}} - C\right)1.8 + 32 \tag{8.7}$$

The calculation methods for a gas stream containing multiple VOCs are complex, particularly when there are significant departures from the ideal behavior of gases and liquids. However, the temperature necessary for condensation of a mixture of VOCs can be estimated by the weighted average of the temperatures necessary to condense each VOC in the gas stream at a concentration equal to the total VOC concentration.[1]

8.3.2 VOC Condenser Heat Load

Condenser heat load is the amount of heat that must be removed from the inlet stream to attain the specified removal efficiency. It is determined from an energy balance, taking into account the enthalpy change due to the temperature change of the VOC, the enthalpy change due to the condensation of the VOC, and the enthalpy change due to the temperature change of the air. Enthalpy change due to the presence of moisture in the inlet gas stream is neglected in the following analysis.

For the purpose of this estimation, it is assumed that, the total heat load on the system is equal to the VOC Condenser heat load. Realistically, when calculating refrigeration capacity requirements for low temperature cooling units, careful consideration should be given to the, process line, losses and heat input of the process pumps. Refrigeration unit capacities are typically rated in terms of net output and do not reflect any losses through process pumps or process lines.

First, the number of lb-moles of VOC per hour in the inlet stream must be calculated by the following expression:

$$M_{VOC,in} = \frac{Q_{in}}{392}\left(Y_{VOC,in}\right) 60 \qquad (8.8)$$

where $M_{voc,in}$ is the molar flow rate of VOC in the inlet stream. The factor 392 is the volume (ft^3) occupied by one lb-mole of inlet gas stream at standard conditions (77°F and 1 atm). The number of lb-moles of VOC per hour in the outlet gas stream is calculated as follows:

$$M_{voc,out} = M_{voc,in}(1-\eta) \qquad (8.9)$$

where $M_{voc,out}$ is the molar flow rate of VOC in the exit stream. Finally, the number of lb-moles of VOC per hour that are condensed is calculated as follows:

$$M_{voc,con} = M_{voc,in} - M_{voc,out} \qquad (8.10)$$

where $M_{voc,con}$ is the flow rate of the VOC that is condensed.

The condenser heat load is then calculated by the following equation:

$$H_{load} = \Delta H_{con} + \Delta H_{uncon} + \Delta H_{noncon} \qquad (8.11)$$

where
H_{load} = condenser heat load (Btu/hr)
ΔH_{con} = enthalpy change associated with the condensed VOC (Btu/hr)
ΔH_{uncon} = enthalpy change associated with the uncondensed VOC (Btu/lir)
ΔH_{noncon} = enthalpy change associated with the noncondensible

air (Btu/hr).

Tile change in enthalpy of the condensed VOC is calculated as follows:

$$\Delta H_{con} = M_{VOC,con} \left[\Delta H_{VOC} - C_{p,VOC}(T_{in} - T_{con}) \right] \tag{8.12}$$

where ΔH_{voc} is the molar heat of condensation and $C_{p,voc}$ is the molar heat capacity of the VOC. Each parameter varies as function of temperature. In Equation 8.12, ΔH_{voc} and $C_{p,voc}$ are evaluated at the mean temperature, *i.e.,* $(T_{in} + T_{con})/2$.

The heat of condensation at a specific temperature, T_2, (°R), can be calculated from the heat of condensation at a reference temperature, T_1 (°R), using the Watson Equation:[7]

$$(\Delta H_{VOC} \ at \ T_2) = (\Delta H_{VOC} \ at \ T_1) \left(\frac{1 - T_2/T_c}{1 - T_1/T_c} \right)^{0.38} \tag{8.13}$$

where T_c (°R) is the VOC critical temperature.

The heat capacity can also be calculated for a specific temperature, T_2, if heat capacity constants (*a, b, c,* and *d*) are known for the particular compound. The heat capacity equation is:

$$C_{p,voc} = a + bT_2 + cT_2^2 + dT_2^3 \tag{8.14}$$

However, to simplify the heat load analysis, *Cp,voc* can be assumed to remain constant over the temperature range of operation *(i.e., T_{in} - T_{con})* without much loss of accuracy in the heat load calculations, as the sensible heat change in Equation 8.12 is relatively small compared to the enthalpy change due to condensation.

Heat of condensation and heat capacity data are provided in Appendix 8A. The heat of condensation for each compound is reported at its boiling point, while its heat capacity is given at 77°F. To estimate the heat of condensation at another temperature, use Equation 8.13. However, the Appendix 8A heat capacity data may be used to approximate $C_{p,voc}$ at other temperatures, since sensible heat changes are usually small, compared to condensation enthalpy changes.

The enthalpy change associated with the uncondensed VOC is calculated by the following expression:

$$\Delta H_{uncon} = M_{VOC,out} \ C_{p,VOC}(T_{in} - T_{con}) \tag{8.15}$$

Finally, the enthalpy change of the noncondensible air is calculated as follows:

$$\Delta H_{noncon} = \left[\left(\frac{Q_{in}}{392} \, 60 \right) - M_{VOC,in} \right] C_{p,air} (T_{in} - T_{con}) \tag{8.16}$$

where $C_{p,air}$ is the specific heat of air. In both Equations 8.15 and 8.16, the C_p's are evaluated at the mean temperature, $(T_{in} + T_{con})/2$.

8.3.3 Condenser Size

Condensers are sized based on the heat load, the logarithmic mean temperature difference between the emission and coolant streams, and the overall heat transfer coefficient. The overall heat transfer coefficient, U, can be estimated from individual heat transfer coefficients of the gas stream and the coolant. The overall heat transfer coefficients for tubular heat exchangers where organic solvent vapors in noncondensible gas are condensed on the shell side and water/brine is circulated on the tube side typically range from 20 to 60 Btu/hr-ft^2-°F according to Perry's *Chemical Engineers' Handbook*[4]. To simplify the calculations, a single *"U"* value may be used to size these condensers. This approximation is acceptable for purposes of making study cost estimates.

Accordingly, an estimate of 20 Btu/hr-ft^2-°F can be used to obtain a conservative estimate of condenser size. The following equation is used to determine the required heat transfer area:

$$A_{con} = \frac{H_{load}}{U \Delta T_{lm}} \tag{8.17}$$

where

A_{con} = condenser surface area (ft^2)
U = overall heat transfer coefficient (Btu/hr-ft^2-°F)
ΔT_{lm} = logarithmic mean temperature difference (°F).

The logarithmic mean temperature difference is calculated by the following equation, which is based on the use of a countercurrent flow condenser:

$$\Delta T_{lm} = \frac{(T_{in} - T_{cool,out}) - (T_{con} - T_{cool,in})}{\ln\left(\dfrac{T_{in} - T_{cool,out}}{T_{con} - T_{cool,in}} \right)} \tag{8.18}$$

where

$T_{cool,in}$ = coolant inlet temperature (°F)
$T_{cool,out}$ = coolant outlet temperature (°F).

The temperature difference ("approach") at the condenser exit can be assumed to be 15°F. In other words, the coolant inlet temperature, $T_{cool,in}$, will be 15°F less than the calculated condensation temperature, T_{con}. Also, the temperature rise of the coolant is specified as 25°F. (These two temperatures- the condenser approach and the coolant temperature rise-reflect good design practice that, if used, will result in an acceptable condenser size.) Therefore, the following equations can be applied to determine the coolant inlet and outlet temperature:

$$T_{cool,in} = T_{con} - 15 \qquad (8.19)$$
$$T_{cool,out} = T_{cool,in} + 25 \qquad (8.20)$$

8.3.4 Coolant Flow Rate

The heat removed from the emission stream is transferred to the coolant. By a simple energy balance, the flow rate of the coolant can be calculated as follows:

$$W_{cool} = \frac{H_{load}}{C_{p,cool} (T_{cool,out} - T_{cool,in})} \qquad (8.21)$$

where W_{cool} is the coolant flow rate (lb/hr), and $C_{p,cool}$ is the coolant specific heat (Btu/lb-°F). $C_{p,cool}$ will vary according to the type of coolant used. For a 50-50 (volume %) mixture of ethylene glycol and water, $C_{p,cool}$ is approximately 0.65 Btu/lb-°F. The specific heat of brine (salt water), another commonly used coolant, is approximately 1.0 Btu/lb-°F.

8.3.5 Refrigeration Capacity

The refrigeration unit is assumed to supply the coolant at the required temperature to the condenser. The required refrigeration capacity is expressed in terms of refrigeration tons as follows:

$$R = \frac{H_{load}}{12,000} \qquad (8.22)$$

Again, as explained In section 8.3.2, H_{load} does not include any heat losses.

8.3.6 Recovered VOC

The mass of VOC recovered in the condenser can be calculated using the following expression:

$$W_{voc,con} = M_{voc,con} \text{ x } MW_{voc} \tag{8.23}$$

where

$W_{voc,con} =$ mass of VOC recovered (or condensed) (lb/hr)
$MW_{voc} =$ molecular weight of the VOC (lb/lb-mole).

8.3.7 Auxiliary Equipment

The auxiliary equipment for a refrigerated surface condenser system may include:

- precooler,
- recovered VOC storage tank,
- pumps/blowers, and
- piping/ductwork.

If water vapor is present in the treated gas stream, a precooler may be needed to remove moisture to prevent ice from forming in the VOC condenser. Sizing of a precooler is influenced by the moisture concentration and the temperature of the emission stream. As discussed in Section 8.2.3, a precooler may not be necessary for intermittently operated refrigerated surface condenser systems where the ice will have time to melt between successive operating periods.

If a precooler is required, a typical operating temperature is 35 to 40°F. At this temperature, almost all of the water vapor present will be condensed without danger of freezing. These condensation temperatures roughly correspond to a removal efficiency range of 70 to 80 percent if the inlet stream is saturated with water vapor at 77°F. The design procedure outlined in the previous sections for a VOC condenser can be used to size a precooler, based on the psychometric chart for the air-water vapor system (see Reference [4]).

Storage/recovery tanks are used to store the condensed VOC when direct recycling is not a suitable option. The size of these tanks is determined from the amount of VOC condensate to be collected and the amount of time necessary before unloading. Sizing of pumps and blowers is based on the liquid and gas flow rates, respectively, as well as the system pressure drop between the inlet and outlet. Sizing of the piping and ductwork (length and diameter) primarily depends upon the stream flow rate, duct/pipe velocity, available space, and system layout.

8.3.8 Alternate Design Procedure

In some applications, it may be desirable to size and cost a refrigerated condenser system that will use a specific coolant and provide a particular condensation temperature. The design procedure to be implemented in such a case would essentially be the same as the one presented in this section

except that instead of calculating the condenser exit temperature needed to obtain a specified VOC recovery efficiency, the exit temperature is given and the corresponding recovery efficiency is calculated.

The initial calculation would be to estimate the partial (= vapor) pressure of the VOC at the given condenser exit temperature, T_{con}, front Equation 8.6. Next, calculate η using Equation 8.24, which is Equation 8.5 rearranged:

$$\eta = \frac{(760\, y_{VOC,in}) - P_{VOC}}{y_{VOC,in}(760 - P_{VOC})}$$ (8.24)

Finally, substitute the calculated P_{voc} into this equation to obtain η. In the remainder of the calculations to estimate condenser heat load, refrigeration capacity, coolant flow rate, etc., follow the procedure presented in Sections 8.3.2 through 8.3.7.

8.4 Estimating Total Capital Investment

This section presents the procedures and data necessary for estimating capital costs for refrigerated surface condenser systems in solvent vapor recovery and gasoline vapor recovery applications. Costs for packaged and nonpackaged solvent vapor recovery systems are presented in Sections 8.4.1 and 8.4.2, respectively. Costs for packaged gasoline vapor recovery systems are described in Section 8.4.3. Costs are calculated based on the design/sizing procedures discussed in Section 8.3.

Total capital investment, TCI, includes equipment cost, EC, for the entire refrigerated condenser unit, auxiliary equipment costs, taxes, freight charges, instrumentation, and direct, and indirect installation costs. All costs in this chapter are presented **3rd quarter 1990 dollars**.[*]

For these control systems, the total capital investment is a battery limit cost estimate and does not include the provisions for bringing utilities, services, or roads to the site; the, backup facilities; the land; the working capital, the research and development required; or the process piping and instrumentation interconnections that may be required in the process generating tile waste gas. These costs are based on new plant installations; no retrofit cost considerations are included. The retrofit cost factors are so site specific that no attempt has been made to provide them.

The expected accuracy of the cost estimates presented in this chapter is ± 30 percent (*i.e.*, "study" estimates). It must be kept in mind that even for a given application, design and manufacturing procedures vary from vendor to vendor, so costs may vary.

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* For information on escalating these prices to more current dollars, refer to the EPA report *Escalation Indexes for Air Pollution Control Costs* and updates thereto, all of which are installed on the OAQPS Technology Transfer Network (CTC Bulletin Board).

In the next two sections, equipment costs are presented for packaged and nonpackaged (custom) solvent vapor recovery systems. respectively. With the packaged systems the equipment cost is factored from the refrigeration the custom systems, the equipment cost is determined as the sum of the costs of the individual system components. Finally. equipment costs for packaged gasoline, vapor recovery systems are given in Section 8.4.3.

8.4.1 Equipment Costs for Packaged Solvent Vapor Recovery Systems

Vendors were asked to provide refrigerated unit cost estimates for a wide range of applications. The equations shown below for refrigeration unit equipment costs, EC_r, are multivariable regressions of data provided by two vendors and are only valid for the ranges listed in Table 8.2.[8,9] In this table, the capacity range of refrigeration units for which cost data were available are shown as a function of temperature.

<u>Single Stage Refrigeration Units (less than 10 tons)</u>

$$Ec_r = \exp{(9.83 - 0.014 T_{con} + 0.340 \ln R)} \qquad (8.25)$$

Table 8.2: Applicability Ranges for the Refrigeration Unit Cost Equations
(Equations 8.25 to 8.27)

Temperature T_{con}(°F)[a]	Minimum Size Available R(tons)		Maximum Size Available R(tons)	
	Single Stage	Multistage	Single Stage	Multistage
40	0.85	NA[b]	174	NA
30	0.63	NA	170	NA
20	0.71	NA	880	NA
10	0.44	NA	200	NA
0 to -5	0.32	NA	133	NA
-10	0.21	3.50	6.6	81
-20 to -25	0.13	2.92	200	68
-30	NA	2.42	NA	85
-40	NA	1.92	NA	68
-45 to -50	NA	1.58	100[c]	55
-55 to -60	NA	1.25	100[c]	100
-70	NA	1.33	NA	42
-75 to -80	NA	1.08	NA	150
-90	NA	0.83	NA	28
-100	NA	0.67	NA	22

[a]For condensation temperatures that lie between the levels shown, round off to the nearest level (*e.g.*, if T_{con} = 16°F, use 20°F) to determine minimum and maximum available size.
[b]NA = System not available based on vendor data collected in this study.
[c]Only one data point available.

Single Stage Refrigeration Units (greater than or equal to 10 tons)

$$EC_\tau = \exp(9.26 - 0.007T_{con} + 0.627\ln R) \tag{8.26}$$

Multistage Refrigeration Units

$$EC_\tau = \exp(9.73 - 0.012T_{con} + 0.584\ln R) \tag{8.27}$$

NOTE: $\exp(a) = e^a \approx 2.718^a$

Equations 8.25 and 8.26 provide costs for refrigeration units based on single stage designs, while Equation 8.27 gives costs for multistage units. Equation 8.27 covers both types of multistage units, "cascade" and "compound". Data provided by a vendor show that the costs of cascade and compound units compare well, generally differing by less than 30%.[8] Thus, only one cost equation is provided. Equation 8.25 applies to single stage refrigeration units smaller than 10 tons and Equation 8.26 applies to single stage refrigeration units as large or larger than 10 tons. Single stage units typically achieve temperatures between 40 and -20°F, although there are units that are capable of achieving -60°F in a single stage.[8, 10] Multistage units are capable of lower temperature operation between -10 and -100°F.
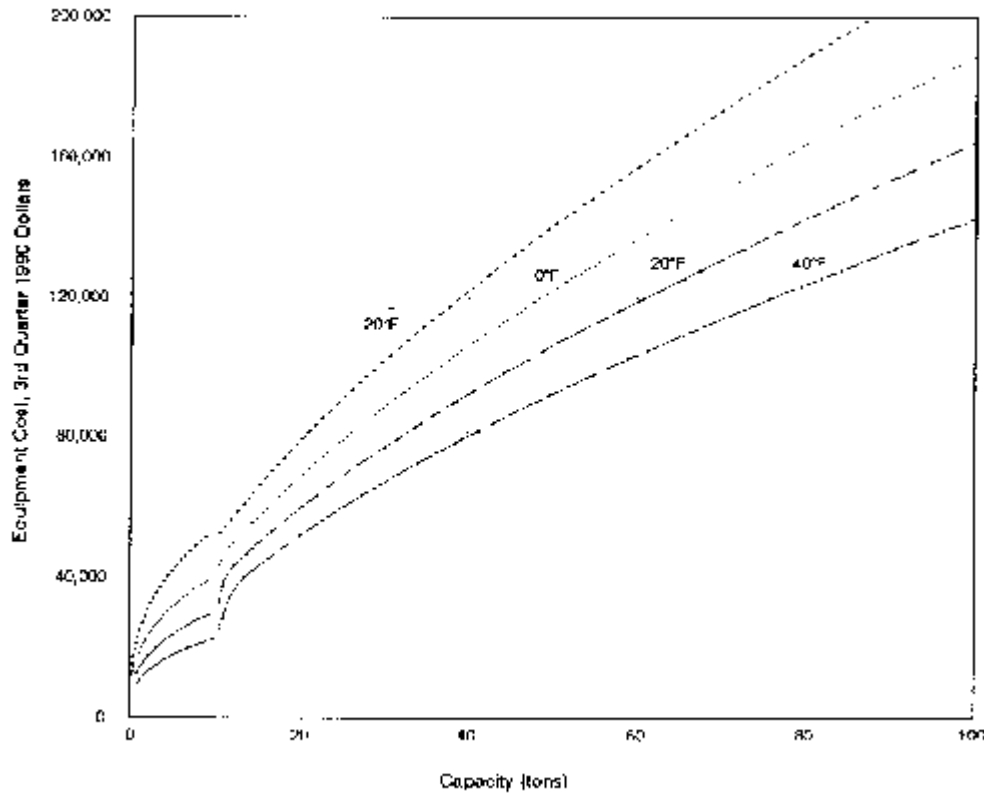

Figure 8.5: Refrigeration Unit Equipment Cost (Single Stage)[8,9]

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Single stage refrigeration unit costs are depicted graphically for selected temperatures in Figure 8.5. Figure 8.6 shows the equipment cost curves for multistage refrigeration units.

(NOTE: In Figure 8.5, the discontinuities in the curves at the 10 ton capacity are a result of the two regression equations used. Equation 8.25 is used for capacities of less than 10 tons; Equation 8.26 is used for capacities greater than or equal to 10 tons.)

These costs are for outdoor models that are skid-mounted on steel beams and consist of the following components: walk-in weatherproof enclosure, air-cooled low temperature refrigeration machinery with dual pump design, storage reservoir, control panel and instrumentation, vapor condenser, and necessary piping. AR refrigeration units have two pumps: a system pump and a bypass pump to short-circuit the vapor condenser during no-load conditions. Costs for heat transfer fluids (brine) are not included.

VOC condenser, recovery tank, the necessary connections, piping, and additional instrumentation. Thus,
The equipment cost of packaged solvent vapor recovery systems (EC_p) is estimated to be 25 percent greater than the cost of the refrigeration unit alone [9]. The additional cost includes the

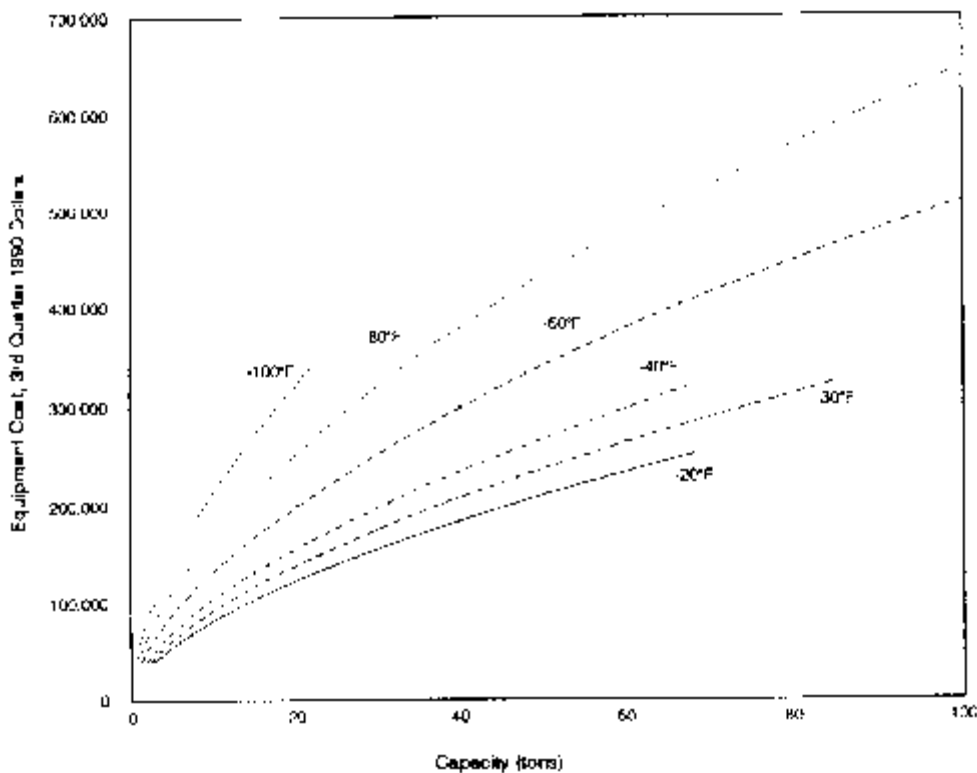$$EC_p = 1.25EC_r \tag{8.28}$$

Figure 8.6: Refrigeration Unit Equipment Cost (Multistage) [9]

Purchased equipment cost, PEC, includes the packaged equipment cost, EC_p, and factors for sales taxes (0.03) and freight (0.05). Instrumentation and controls are included with the packaged units. Thus,

$$PEC_p = Ec_p (1 + 0.03 + 0.05) = 1.08EC_p \qquad (8.29)$$

8.4.2 Equipment Costs for Nonpackaged (Custom) Solvent Vapor Recovery Systems

To develop cost estimates for nonpackaged or custom refrigerated systems, information was solicited from vendors on costs of refrigeration units, VOC condensers, and VOC storage/recovery tanks [9, 11, 12]. Quotes from the vendors were used to develop the estimated costs for each type of equipment. Only one set of vendor data was available for each type of equipment.

Equations 8.25, 8.26, and 8.27 shown above are applicable for estimating the costs for the *refrigeration units.*

Equation 8.30 shows the equation developed for the *VOC condenser* cost estimates[11]:

$$EC_{con} = 34A_{con} + 3,775 \qquad (8.30)$$

This equation is valid for the range of 38 to 800 ft^2 and represents costs for shell arid tube type heat exchangers with 304 Stainless Steel tubes.

The following equation represents the *storage/recovery tank* cost data obtained from one vendor[12]:

$$EC_{tank} = 2.72V_{tank} + 1,960 \qquad (8.31)$$

These costs are applicable for the range of 50 to 5,000 gallons and pertain to 316 stainless steel vertical tanks.

Costing procedures for a precooler (EC_{pre}) that includes a separate condenser/refrigeration unit and a recovery tank are similar to that for a custom refrigerated condenser system. Hence, Equations 8.25 through 8.31 would be applicable, with the exception of Equation 8.27, which represents multistage systems. Multistage systems operate at much lower temperatures than that required by a precooler.

Costs for auxiliary equipment such as ductwork, piping, fans, or pumps are designated as ECauz, These items should be costed separately using methods described elsewhere in this Manual.

The total equipment cost for custom systems, EC_c is then expressed as:

$$EC_c = EC_r + EC_{con} + EC_{tank} + EC_{pre} + EC_{aux} \qquad (8.32)$$

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The purchased equipment cost including EC_c and factors for sales taxes (0.03), freight (0.05), and instrumentation and controls (0.10) is given below:

$$PEC_c = EC_c(1 + 0.03 + 0.05 + 0.10) = 1.18EC_c \qquad (8.33)$$

8.4.3 Equipment Costs for Gasoline Vapor Recovery Systems

Separate quotes were obtained for packaged gasoline vapor recovery systems because these systems are specially designed for controlling gasoline vapor emissions from such sources as storage tanks, gasoline bulk terminals, and marine vessel loading and unloading operations. Systems that control marine vessel gasoline loading and unloading operations also must meet U.S. Coast Guard safety requirements.

Quotes obtained from one vendor were used to develop equipment cost estimates for these packaged systems (see Figure 8.7. The cost equation shown below is a least squares regression of these cost data and is valid for tile range 20 to 140 tons.[91

$$EC_p = 4,910R + 212,000 \qquad (8.34)$$

The vendor data in process flow capacity (gal/min) vs cost ($) were transformed into Equation 8.34 after applying the design procedures in Section 8.3. Details of the data transformation are given in Appendix 8B.

The cost estimates apply to skid-mounted refrigerated VOC condenser systems for hydrocarbon vapor recovery primarily at gasoline loading/storage facilities. The systems are intermittently operated at -80 to -120°F allowing 30 to 60 minutes per day for defrosting by circulation of warm brine. Multistage systems are employed to achieve these lower temperatures. Tile achievable VOC removal efficiencies for these systems are in the range of 90 to 95 percent.

The packaged systems include the refrigeration unit with the necessary pumps, compressors, condensers/evaporators, coolant reservoirs, the VOC condenser unit and VOC recovery tank, precooler, instrumentation and controls, and piping. Costs for heat transfer fluids (brines) are not included. The purchased equipment cost for these systems includes sales tax and freight and is calculated using Equation 8.29.

8.4.4 Installation Costs

The total capital investment, TCl, for packaged systems is obtained by multiplying the purchased equipment cost, PEC_p by the total installation factor:[13]

$$TCI = 1.15 PEC_p \quad (8.35)$$

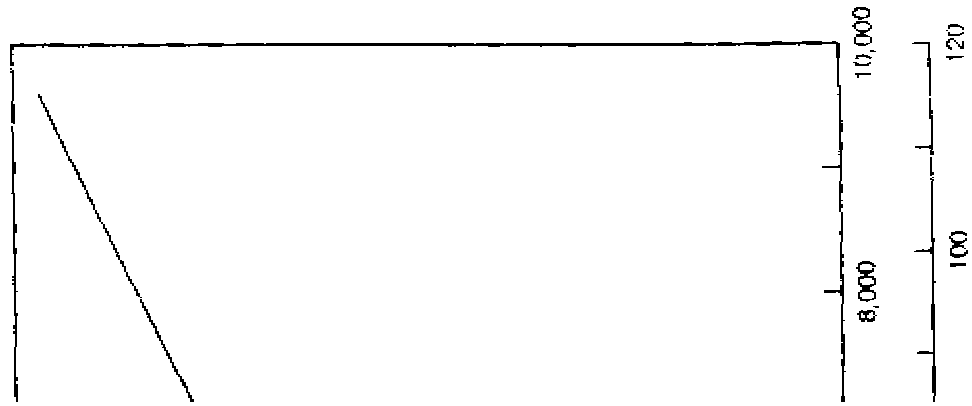For nonpackaged (custom) systems, the total inst

Figure 8.7: Gasoline Vapor Recovery System Equipment Cost[9]

8-24

allation factor is 1.74:

Table 8.3: Capital Cost Factors for Nonpackaged (Custom) Refrigerated Condenser Systems

Cost Item	Factor
Direct Costs	
Purchased equipment costs	
Refrigerated condenser system, EC	As estimated, A
Instrumentation	0.10 A
Sales taxes	0.03 A
Freight	0.05 A
Purchased equipment cost, PEC	B = 1.18 A[a]
Direct installation costs	
Foundations & supports	0.08 B
Handling & erection	0.14 B
Electrical	0.08 B
Piping	0.02 B
Insulation	0.10 B
Painting	0.01 B
Direct installation costs	0.43 B
Site preparation	As required, SP
Buildings	As required, Bldg.
Total Direct Costs, DC	1.43 B + SP + Bldg.
Indirect Costs (installation)	
Engineering	0.10 B
Construction and field expenses	0.05 B
Contractor fees	0.10 B
Start-up	0.02 B
Performance test	0.01 B
Contingencies	0.03 B
Total Indirect Costs, IC	0.31 B
Total Capital Investment = DC + IC	1.74 B + SP + Bldg.[b]

))

[a]Purchased equipment cost factor for packaged systems is 1.08 with instrumentation included.

[b]For packaged systems, total capital investment $= 1.15 PEC_p$

Table 8.4: Suggested Annual Cost Factors for Refrigerated Condenser Systems

Cost Item	Factor
Direct Annual Costs, DC	
Operating Labor	
Operator	1/2 hour per shift
Supervisor	15% of operator
Operating materials	—
Maintenance	
Labor	1/2 hour per shift
Material	100% of maintenance labor
Electricity[9]	
at $40°F$	1.3 kW/ton
at $20°F$	2.2 kW/ton
at $-20°F$	4.7 kW/ton
at $-50°F$	5.0 kW/ton
at $-100°F$	11.7 kW/ton
Indirect Annual Costs, IC	
Overhead	60% of total labor and maintenance material costs
Administrative charges	2% of Total Capital Investment
Property tax	1% of Total Capital Investment
Insurance	1% of Total Capital Investment
Capital recovery[a]	0.1098 x Total Capital Investment
Recovery Credits, RC	
Recovered VOC	Quantity recovered x operating hours
Total Annual Cost	DC + IC - RC

[a]Assuming a 15 year life at 7%[13]. See Chapter 2.

$$TCI = 1.74PEC_c \qquad (8.36)$$

An itemization of tile total installation factor for nonpackaged systems is shown in Table 8.3. Depending on the site conditions., the installation costs for a given system could deviate significantly, from costs generated by there average factors. Guidelines are available for adjusting these average installation factors.[14]

8.5 Estimating Total Annual Cost

The total annual cost (TAC) is the sum of the direct and indirect annual costs. The bases used in calculating annual cost factors are given in Table 8.4

8.5.1 Direct Annual Costs

Direct annual costs, DC, include-labor (operating and supervisory), maintenance (labor and materials), and electricity.

Operating labor is estimated at 1/2-hour per 8-hour shift. The supervisory labor cost is estimated at 15% of the operating labor cost. Maintenance labor is estimated at 1/2-hour per 8-hour shift. Maintenance materials costs are assumed to equal maintenance labor costs.

Utility costs for refrigerated condenser systems include electricity requirements for the refrigeration unit and any pumps/blowers. The power required by the pumps/blowers is negligible when compared with the refrigeration unit power requirements. Electricity requirements for refrigerated condenser systems are summarized below:

Electricity (E, kW/ton)	Temperature (°F)
1.3	40
2.2	20
4.7	-20
5.0	-50
11.7	-100

These estimates were developed from product literature obtained from one vendor.[9] The electricity cost, C_e, can then be calculated from the following expression:

$$C_e = \frac{R}{0.85} E \theta_s \ p_e \qquad (8.37)$$

where
- θ_s = system operating hours (hr/yr)
- p_e = electricity cost

The factor 0.85 accounts for the mechanical efficiency of the compressor.[1]

8.5.2 Indirect Annual Costs

Indirect annual costs, IC, are calculated as the sum of capital recovery costs plus general and administrative (G&A), overhead, property tax, and insurance costs. Overhead is assumed to be equal to 60 percent of the sum of operating, supervisory, and maintenance labor, and maintenance materials. Overhead cost is discussed in Chapter 2 of this *Manual.*

The system capital recovery cost, CRC, is based on an estimated 15-year equipment life.[13] (See Chapter 2 of the *Manual* for a discussion of the capital recovery cost.) For a 15-year life and an interest rate of 7 percent, the capital recovery factor is 0.1098. The system capital recovery cost is then estimated by:

$$CRC = 0.1098\,TCI \qquad (8.38)$$

G&A costs, property tax, and insurance are factored from total capital investment. typically at 2 percent, 1 percent, and 1 percent, respectively.

8.5.3 Recovery Credit

If the condensed VOC can be directly reused or sold without further treatment, then the credit from this operation is incorporated in the total annual cost estimates. The following equation can be used to estimate the VOC, recovery credit, RC:

$$RC = W_{voc,con}\ \theta_s p_{voc} \qquad (8.39)$$

where
- p_{voc} = resale value of recovered VOC ($/lb)
- $W_{voc,con}$ = quantity of VOC recovered (lb/hr).

8.5.4 Total Annual Cost

The total annual cost (TAC) is calculated as the sum of the direct and indirect annual costs, minus the recovery credit:

$$TAC = DC + IC - RC \qquad (8.40)$$

8.6 Example Problem #1

The example problem described in this section shows how to apply the refrigerated condenser system sizing and costing procedures to the control of a vent stream consisting of acetone, air, and a negligible amount of moisture. This example problem assumes a required removal efficiency and calculates the temperature needed to achieve this level of control.

8.6.1 Required Information for Design

The first step in the design procedure is to specific the gas stream to be processed. Gas stream parameters to be used in this example problem are listed in Table 8.5. The values for the Antoine equation constants, heat, of condensation, and heat capacity of acetone are obtained from Appendix 8A. Specific heat of the coolant is obtained from Perry's *Chemical Engineers' Handbook[4].*

8.6.2 Equipment Sizing

The first step in refrigerated condenser sizing is determining the partial pressure of the VOC at the outlet of the condenser for a given removal efficiency. Given the stream flow rate, inlet VOC concentration, and the required removal efficiency, the partial pressure of the VOC at the outlet can be calculated using Equation 8.5.

$$P_{VOC} = 760 \, \frac{0.375(1 - 0.90)}{(1 - 0.375(0.90)} = 43 \text{ mm Hg}$$

Next, the temperature necessary to condense the required amount of VOC must be determined using Equation 8.7:

$$T_{con} = \left(\frac{1210.595}{7.117 - \log_{10} 43} - 229.664 \right) 1.8 - 32 = 16 \,^{\circ}F$$

Table 8.5: Example Problem Data

Vent Stream Parameters

Inlet Stream Flow Rate	100 scfm[a]
Inlet Stream Temperature	86°F
VOC to be Condensed	Acetone
VOC Inlet Volume Fraction	0.0375
Required VOC Removal Efficiency	.90

Antoine Equation Constants for Acetone:

A	7.117
B	1210.595
C	229.664
Heat of Condensation of Acetone[b]	12,510 Btu/lb-mole
Heat Capacity of Acetone[c]	17.90 Btu/lb-mole-°F
Specific Heat of Coolant[c] (ethylene glycol)	0.65 Btu/lb-°F
Heat Capacity of Air[c]	6.95 Btu/lb-mole-°F

Annual Cost Data Assumed

Operating Labor	$15.64/hr
Maintenance Labor	$17,2/hr
Electricity	$0.0461/kWh
Acetone Resale Value	$0.10/lb

[a]Standard conditions: 77°F and 1 atmosphere.
[b]Evaluated at the acetone boiling point (134°F).
[c]These properties were evaluated at 77°F.

The next step is to estimate the VOC condenser heat load. Calculate: (1) the VOC flow rate for the inlet/outlet emission streams, (2) the flow rate of the condensed VOC, and (3) the condenser heat balance. The flow rate of VOC in the inlet stream is calculated from Equation 8.8.

$$M_{VOC,\,in} = \frac{100}{393}\ (0.375)\ 60\ = 5.74\ \text{lb moles/hr}$$

The flow rate of VOC in the outlet stream is calculated using Equation 8.9 as follows:

$$M_{voc,out} = 5.74\,(1 - 0.90) = 0.574\ \text{lb-moles/hr}$$

Finally, the flow rate of condensed VOC is calculated with Equation 8.10:

$$M_{voc,con} = 5.74 - 0.574 = 5.166\ \text{lb-moles/hr}$$

Next, the condenser heat balance is conducted. As indicated in Table 8.5, the acetone heat of condensation is evaluated at its boiling point, 134°F. However, it is assumed (for simplicity) that all of the acetone condenses at the condensation temperature, $T_{con} = 16$°F. To estimate the heat of condensation at 16°F, use the Watson equation (Equation 8.13) with the following inputs: $T_c = 918$°R(Appendix 8A); $T_1 = 134 + 460 = 594$°R; $T_2 = 16 + 460 = 476$°R. Upon substitution, we obtain:

$$(\Delta H_{VOC}\ \text{at}\ 16\,°F)\ = 12{,}510\left(\frac{1\ -476/918}{1\ -594/918}\right)^{0.38}$$

$$= 14{,}080\ \text{Btu/lb mole}$$

As Table 8.5 shows, the heat capacities of acetone and air and the specific heat of the, coolant were all evaluated at, 77°F. This temperature is fairly close to the condenser mean operating temperature, *i.e.*, (86 + 16)/2 = 51°F. Consequently, using tile 77°F values would not add significant additional error to the heat load calculation.

The change in enthalpy of the condensed VOC is calculated using Equation 8.12:

$$\Delta H_{con} = 5.166\,[14{,}080 + 17.90(86 - 16)] = 79{,}210\ \text{Btu/hr}$$

The enthalpy change associated with the uncondensed VOC is calculated from Equation 8.15:

$$\Delta H_{uncon} = (0.574)(17.90)(86 - 16) = 719\ \text{Btu/hr}$$

Finally, the enthalpy change of the noncondensible air is estimated from Equation 8.16:

$$\Delta H_{noncon} = \left[\left(\frac{100}{392}60\right) - 5.74\right]6.95(86 - 16) = 4,654 \text{ Btu/hr}$$

The condenser heat load is then calculated by substituting ΔH_{con}, ΔH_{uncon}, and ΔH_{noncon} in Equation 8.11:

$$H_{load} = 79,210 + 719 + 4,654 = 84,583 \text{ Btu/hr}$$

The next step is estimation of the VOC condenser size. The logarithmic mean temperature difference is calculated using Equation 8.18. In this calculation, $T_{cool,in}$ = 16 - 15 = 1°F and $T_{cool,out}$ = 1 + 25 = 26°F from Equations 8.19 and 8.20, respectively:

$$\Delta T_{lm} = \frac{(86 - 26) - (16 - 1)}{\ln\left(\frac{86 - 26}{16 - 1}\right)} = 32.5 °F$$

The condenser surface area can then be calculated using Equation 8.17.

$$A_{con} = \frac{84,583}{20(32.5)} = 130 \text{ ft}^2$$

In this equation, a conservative value of 20 Btu//hr-ft²-°F is used as the overall heat transfer coefficient.

The coolant flow rate can be calculated using Equation 8.21.

$$W_{cool} = \frac{84,583}{0.65(26 - 1)} = 5,205 \text{ lb/hr}$$

The refrigeration capacity can be estimated from Equation 8.22 as follows:

$$R = \frac{84,583}{12,000} = 7.05 \text{ tons}$$

Finally, the quantity of recovered VOC can be estimated using Equation 8.23:

$$W_{voc,con} = 5.166 \times 58.08 = 300 \text{ lb/hr}$$

where the molecular weight of acetone is obtained from Appendix 8A.

Note that in this example case, the partial pressure of acetone at the condenser exit is relatively high (43 mm Hg). In applications where much lower outlet concentrations are desired, a second control device (e.g., incinerator, adsorber) to operate in series with the condenser may need to be considered.

8.6.3 Equipment Costs

Once the system sizing parameters have been determined, the equipment costs can be calculated. For the purpose of this example, a custom refrigerated condenser system, including a refrigeration unit, a VOC condenser, and a recovery tank will be costed.

From Table 8.2, a single stage refrigeration unit appears to be suitable for the example problem with an estimated condensation temperature of 16°F and capacity of 7.05 tons. Hence Equation 8.25, which is applicable to units less than 10 tons. is selected for estimating costs. Application of this equation results in the following value for the refrigeration unit cost:

$$EC_\tau = \exp\,[9.83 - 0.014(16) + 0.340\ln(7.05)] = \$28,855$$

VOC condenser cost is computed using Equation 8.30 as follows:

$$EC_{con} = 34(130) + 3,775 = \$8,195$$

Recovery tank cost can be calculated from Equation 8.31. For this case, $W_{voc,con}$ = 300 lb/hr, which is equivalent to 45.5 gal/hr (density of acetone is about 6.6 lb/gal). Assuming an 8-hour daily operation, the interim storage capacity requirement would be 364 gallons. Application of Equation 8.31 leads to the following:

$$EC_{tank} = 2.72(364) + 1,960 = \$2,950$$

Assuming there are no additional costs due to precooler or other auxiliary equipment, the total equipment cost is calculated from Equation 8.32:

$$EC_c = 28,855 + 8,195 + 2,950 + 0 + 0 = \$40,000$$

The purchased equipment cost including instrumentation, controls, taxes, and freight is estimated using Equation 8.33:

$$PEC_c = 1.18(40,000) = \$47,200$$

The total capital investment is calculated using Equation 8.36:

$$TCI = 1.74(47,200) = \$82,128 \approx \$82,100$$

8.6.4 Total Annual Cost

Table 8.6 summarizes the estimated annual costs for the, example problem. The cost calculations are shown in the table.

Direct annual costs for refrigerated systems include labor, materials, and utilities. Labor costs are based on 8-hr/day, 5-day/week operation. Supervisory labor is computed at 15 percent of operating labor, and operating and maintenance labor are each based on 1/2 hr per 8-hr shift. The electricity cost is based on a requirement of 2.2 kW/ton (see page 8-30), because the condensation temperature (16°F) is close to the 20°F temperature given for this value.

Indirect annual costs include overhead, capital recovery, administrative charges, property tax, and insurance.

Total annual cost is estimated using Equation 8.40. For this example case, application of refrigerated condensation as a control measure results in an annual *savings* of $37,500. As Table 8.6 shows, the acetone recovery credit is over twice the direct and Indirect costs combined. Clearly, this credit has more influence on the total annual cost than any other Component. Although the credit depends on three parameters-the acetone recovery rate, the annual operating hours, and the acetone salvage value ($0.10/lb)-the last parameter is often the most difficult to estimate. This is mainly because the salvage value varies according to the facility location as well as the current state of the chemical market.

8.7   Example Problem #2

In this example problem, the alternate design procedure described in Section 8.3.8 is illustrated. The temperature of condensation is given, and the resultant removal efficiency is calculated. The example stream inlet parameters are identical to Example Problem #1 with the exception that removal efficiency is not specified and the required temperature of condensation is assumed to be 16°F.

8.7.1 Required Information for Design

The first step is to calculate the partial pressure of the VOC at the specified temperature (16°F) using Equation 8.6 to solve for P_{VOC}:

$$\log P_{VOC} = A - \frac{B}{T_{con} - C}$$

Remember to convert T_{con} to degrees Centigrade, *i.e.*, 16°F = -8.9°C.

Table 8.6: Auunal Cost for Refrigerated Condenser System
Example Problem

Cost Item	Calculations	Cost
Direct Annual Costs, DC		
Operating Labor		
Operator	$\dfrac{0.5h}{shift}$ x $\dfrac{shift}{8h}$ x $\dfrac{2,080h}{yr}$ x $\dfrac{\$15.64}{h}$	$2,030
Supervisor	15% of operator = 0.15 x 2,030	300
Operating materials		----
Maintenance		
Labor	$\dfrac{0.5h}{shift}$ x $\dfrac{shift}{8h}$ x $\dfrac{2,080h}{yr}$ x $\dfrac{\$17.21}{h}$	2,240
Material	100% maintenance labor	2,240
Utilities		
Electricity	$\dfrac{7.05tons}{0.85}$ x $\dfrac{2.2kw}{Ton}$ x $\dfrac{2,080h}{yr}$ x $\dfrac{\$0.0461}{kwh}$	1,750
Total DC		$8,560
Indirect Annual Costs, JC		
Overhead	60% of total labor and maintenance material = 0.6 (2,030 + 305 + 2,240 + 2,240)	4,090
Administrative charges	2% of Total Capital Investment =0.02($82,100)	1,640
Property tax	1% of Total Capital Investment =0.01($82,100)	820
Insurance	1% of Total Capital Investment =0.01($82,100)	820
Capital recovery[a]	0.1098 x $82,100	9,010
Total IC		$16,380
Recovery Credits, RC		
Recovered Acetone	$\dfrac{300lb}{h}$ x $\dfrac{2,080h}{yr}$ x $\dfrac{\$0.10}{lb}$	($62,400)
Total Annual Cost (rounded)		($37,500) (Savings)

[a]The capital recovery cost factor, CRF, is function of the refrigerated condenser equipment life and the opportunity cost of the capital (i.e., interest rate). For example, for a 15 year equipment life and a 7% interest rate, CRF = 0.1098.

Substituting the values for the Antoine equation constants for acetone as listed in Table 8.5:

$$\log P_{VOC} = 7.117 - \frac{1210.595}{8.9 + 229.664}$$

$$P_{VOC} = 43 \text{ mm Hg.}$$

Using Equation 8.24, the removal efficiency is:

$$\eta = \frac{[760(0.375)] - 43}{0.375(760 - 43)} = 0.90$$

The remainder of the calculations in this problem are identical to those in Example Problem #1.

8.8 Acknowledgments

The authors gratefully acknowledge the following companies for contributing data to this chapter:

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- ITT Standard (Atlanta, GA)

- XChanger (Hopkins, MN)

- Buffalo Tank Co. (Jacksonville, FL)

Appendix 8A

Properties of-Selected Compounds

Table 8.7: Properties of Selected Compounds

Compound	Critical Temp.[a] (°R)	Boiling Point (°F)	Molecular Weight (lb/lb-mole)	Heat of Condensation[b] (Btu/lb-mole)	Heat Capacity[c] ($\frac{B}{lb\ m}$)	State
Acetone	918	134	58.08	12,510	30.22	Liquid
					17.90	Gas
Acetylene	555	-119	26.02	7,290	10.50	Gas
Acrylonitrile	-	171	53.06	14,040	15.24	Gas
Aniline	1259	364	93.13	19,160	45.90	Liquid
					25.91	Gas
Benzene	1012	176	78.11	13,230	19.52	Liquid
Benzonitrile	1259	376	103.12	19,800	26.07	Gas
Butane	766	31	58.12	9,630	23.29	Gas
Chloroethane	829	54	64.52	10,610	14.97	Gas
Chloroform	966	143	119.39	12,740	15.63	Gas
Chloromethane	750	-12	50.49	9,260	9.74	Gas
Cyclobutane	-	55	56.10	10,410	17.26	Gas
Cyclohexane	997	177	84.16	12,890	37.4	Liquid
					25.40	Gas
Cyclopentane	921	121	70.13	11,740	30.80	Liquid
					19.84	Gas
Cyclopropane	716	-27	42.08	8,630	13.37	Gas
Diethyl ether	840	94	74.12	11,480	40.8	Liquid
					26.89	Gas
Dimethylamine	788	44	45.09	11,390	16.50	Gas
Ethylbenzene	1111	277	106.17	15,300	30.69	Gas
Ethylene oxide	845	51	44.05	10,980	11.54	Gas
Heptane	973	209	100.12	13,640	53.76	Liquid
					39.67	Gas
Hexane	914	156	86.18	12,410	45.2	Liquid
					34.20	Gas
Methanol	923	148	32.04	14,830	19.40	Liquid
					10.49	Gas
Octane	1024	258	114.23	14,810	45.14	Gas
Pentane	846	97	72.15	11,090	28.73	Gas
Toluene	1065	231	92.14	14,270	37.58	Liquid
					24.77	Gas
o - Xylene	1135	292	106.17	15,840	44.9	Liquid
					31.85	Gas
m - Xylene	1111	282	106.17	15,640	43.8	Liquid
					30.49	Gas
p - Xylene	1109	281	106.17	15.480	30.32	Gas

[a]Reprinted with permission from *Lange's Handbook of Chemistry* (12th edition), Table 9-7.[15]
[b]Reprinted with permission from *Lange's Handbook of Chemistry* (12th edition), Table 9-4.[15]
(Measured at boiling point.)
[c]Reprinted with permission from *Lanqe's Handbook of Chemistry* (12th edition), Table 9-2.[15]
(Measured at 77°F.)

Table 8.8: Antoine Equation Constants for Selected Compounds[a]

Compound	Antoine Equation Constants			Valid Temperature Range (°F)
	A	B	C	
Acetone	7.117	1210.595	229.66	Liquid
Acetylene	7.100	711.0	253.4	-116 to -98
Acrylonitrile	7.039	1232.53	222.47	-4 to 248
Aniline	7.320	1731.515	206.049	216 to 365
Benzene	6.905	1211.033	220.790	46 to 217
Benzonitrile	6.746	1436.72	181.0	Liquid
Butane	6.809	935.86	238.73	-107 to 66
Chloroethane	6.986	1030.01	238.61	-69 to 54
Chloroethylene	6.891	905.01	239.48	-85 to 9
Chloroform	6.493	929.44	196.03	-31 to 142
Chloromethane	7.0933	948.58	249.34	-103 to 23
Cyanic acid	7.569	1251.86	243.79	-105 to 21
Cyclobutane	6.916	1054.54	241.37	-76 to 54
Cyclohexane	6.841	1201.53	222.65	68 to 178
Cyclopentane	6.887	1124.16	231.36	-40 to 162
Cyclopropane	6.888	856.01	246.50	-130 to -26
Diethyl ether	6.920	1064.07	228.80	-78 to 68
Diethylamine	5.801	583.30	144.1	88 to 142
Dimethylamine	7.082	960.242	221.67	-98 to 44
Dioxane - 1,4	7.432	1554.68	240.34	68 to 221
Ethyl benzene	6.975	1424.255	213.21	79 to 327
Ethylene oxide	7.128	1054.54	2371.76	-56 to 54
Heptane	6.897	1264.90	216.54	28 to 255
Hexane	6.876	1171.17	224.41	-13 to 198
Methanol	7.897	1474.08	229.13	7 to 149
Octane	6.919	1351.99	209.15	66 to 306
Pentane	6.853	1064.84	233.01	-58 to 136
Toluene	6.955	1344.8	219.48	43 to 279
Vinyl acetate	7.210	1296.13	226.66	72 to 162
o - Xylene	6.999	1474.679	213.69	90 to 342
m - Xylene	7.009	1462.266	215.11	82 to 331
p - XyIene	6.991	1453.430	215.31	81 to 331

Appendix 8B

Documentation for Gasoline Vapor Recovery System Cost Data

As mentioned in Section 8.4.3, vendor cost data were obtained that related the equipment cost ($) of packaged gasoline vapor recovery systems to the process flow capacity (gal/min). These data needed to be transformed, in order to develop Equation 8.34, which relates equipment cost ($) to system refrigeration capacity (R, tons), as follows:

$$EC_p = 4{,}910R + 212{,}000$$

To make this transformation, we needed to develop an expression relating flow capacity to refrigeration capacity. The first step was to determine the inlet partial pressure ($P_{VOC,in}$) of the VOC-gasoline, in this case. As was done in Section 8.3.1, we assumed that the VOC vapor was saturated and, thus, in equilibrium with the VOC liquid. This, in turn, meant that we could equate the partial pressure to the vapor pressure. The "model" gasoline had a Reid vapor pressure of 10 and a molecular weight of 66 lb/lb-mole, as shown in Section 4.3 of *Compilation of Air Pollutant Emission Factors* (FPA publication AP-42, Fourth Edition, September 1985). For this gasoline, the following Antoine equation constants were used:

$$A = 12.5733$$

$$B = 6386.1$$

$$C = 613$$

These constants were obtained by extrapolating available vapor pressure vs. temperature data for gasoline found in Section 4.3 of AP-42. Upon substituting these constants and an assumed inlet temperature of 77°F (25°C) into the Antoine equation and solving for the inlet partial pressure ($P_{voc,in}$) We obtain:

$$\log P_{VOC,in} = A - \frac{B}{T_{in} - C}$$

$$= 12.5733 - \frac{6386.1}{25 - 6 13}$$

$$P_{voc,in} = 366 \, \text{mm Hg}.$$

If the system operates at atmospheric pressure (760 mm Hg), this partial pressure would correspond to a VOC volume fraction in the inlet stream of:

$$y_{VOC,in} = \frac{366 \, \text{mm}}{760 \, \text{mm}} = 0.482$$

The outlet partial pressure ($P_{voc,out}$) and volume fraction are calculated in a similar way. The condensation (outlet) temperature used in these calculations is -80°F (-62°C), the typical operating Temperature for the gasoline vapor recovery units for which the vendor supplied costs.

$$\log P_{VOC,out} = 12.5733 - \frac{6386.1}{62 - 6 13}$$

$$P_{voc,out} = 9.62 \, \text{mm Hg}.$$

This corresponds to a volume fraction in the outlet stream ($y_{voc,out}$) of:

$$y_{VOC,out} = \frac{9.62 \, \text{mm}}{760 \, \text{mm}} = 0.0127$$

Substitution of $P_{VOC,out}$ and $y_{VOC,in}$ into Equation 8.24 yields the condenser removal efficiency (η):

$$\eta = \frac{(760 \, x \, 0.482) - 9.62}{0.482(760 - 9.62)} = 0.986$$

The next step in determining the inlet and outlet VOC hourly molar flow rates ($M_{voc,in}$ and $M_{voc,out}$, respectively). As Equation 8.8 shows, $M_{voc,in}$ is a function of $y_{voc,in}$ and the total inlet volumetric flow rate, Q_{in}, (scfm).

Now, because the gasoline vapor flow rates are typically expressed in gallons/minute, we have to convert them to scfm. This is done as follows:

$$Q_{in} = Q_g \, (\text{gal/min}) \, x \, \frac{1 \, ft^3}{7.48 \, \text{gal}} = 0.134 \, Q_s \, \text{scfm}$$

Substituting these variables into Equation 8.8, we obtain:

$$M_{VOC,in} = \frac{0.134 Q_g}{392} (0.482)60 = 0.00989 Q_g \text{ lb mole/hr}$$

We obtain $M_{VOC,out}$ from Equation 8.9:

$$M_{voc,out} = 0.00989 Q_g (1 - 0.986) = (1.38 \times 10^{-4}) Q_g \text{ lb-moles/hr}$$

And according to Equation 8.10, the amount of gasoline vapor condensed ($M_{voc,con}$) is the difference between $M_{VOC,in}$ and $M_{voc,out}$:

$$M_{VOC,con} = 0.00975 Q_g \text{ lb-moles/hr}$$

The final step is to calculate the condenser heat load. This load is a function of the inlet, outlet, and condensate molar flow rates, the inlet and condensation temperatures, the heat capacities of the VOC and air, and the VOC heat of condensation. The VOC heat capacity and heat of condensation data used are based on pentane and butane chemical properties, the largest components of gasoline, and were obtained from *CHRIS Hazardous Chemical Data* (U.S. Coast Guard, U.S. Department of Transportation, June 1985).

Heat capacities (Btu/Ib-mole-°F):

$$C_{p,VOC} = 26.6$$
$$C_{p,air} = 6.95$$

Heat of condensation of VOC: 9,240 Btu/Ib-mole

Substitution of these data, the molar flow rates, and the temperatures into Equations 8.12, 8.15 and 8.16 yields the following enthalpy changes in Btu/hr:

$$\Delta H_{con} = 130.8 Q_g$$
$$\Delta H_{uncon} = 0.572 Q_g$$
$$\Delta H_{noncon} = 11.6 Q_g$$

The condenser heat load (H_{load}) is the sum of these three enthalpy changes (Equation 8.11):

$$H_{load} = 143 Q_g$$

The refrigeration capacity (R, tons) is computed from Equation 8.22:

$$R = \frac{H_{load}}{12,000} = 0.0119 Q_g$$

This last equation relates the refrigeration capacity (tons) to the inlet gasoline vapor flow rate (gal/min). Solving for Q_g, in terms of R, we obtain:

$$Q_g = 83.9R$$

Finally, we substitute this relationship into the equipment cost ($) vs. vapor flow rate ($Q_g$) correlation, which-was developed from the vendor cost data:

$$
\begin{aligned}
EC_p \quad &= 58.5Q_g + 212{,}000 \\
&= 58.5(83.9R) + 212{,}000 \\
&= 4{,}910R + 212{,}000
\end{aligned}
$$

Note that this last expression is identical to Equation 8.34.

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